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Modelling of Nitrate Leaching on a Regional Scale Using a GIS

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A GIS was used to model nitrate leaching losses to surface waters in Northern Ireland by integrating a number of datasets, including farm and population census data, on a 10 × 10 km grid. This model enabled an estimate to be made of the contribution of agriculture, domestic sewage and rainfall deposition to the amount of nitrate leached from each grid square. The model was also used to predict annual mean nitrate concentrations within each grid square and the predictions validated against data from a statutory river monitoring programme. Predicted annual flow rates and nitrate loadings to watercourses from catchments ranging in size from 14·9 km² to 4453 km² were compared with estimates based on conventional monitoring. In general, the predicted flows and loads agreed with observed values to within ±10% for flow rates and to within ±25% for nitrate loads. This level of prediction is an adequate level on which to base management decisions covering possible designation under EC directives. The model predicted that losses of nitrate from agriculture accounted for around 70% of the annual total nitrate load to a major watercourse. In the eastern counties of Northern Ireland, rainfall and domestic sewage made approximately equal contributions to the remaining 30% of the nitrate leached. However, in the less heavily populated western counties of Northern Ireland, the contribution from rainfall to the amount of nitrate leached was around five times that from domestic sewage.

Keywords: GIS, nitrate leaching, agriculture, modelling, catchment management.

1. Introduction

The rising concentration of nitrate in many of the surface waters of the U.K. (Smith *et al.*, 1982; Smith and Stewart, 1989; Johnes and Burt, 1993) has been a long-standing source of concern. Although concentrations within major rivers in Northern Ireland currently comply with the E.C. Drinking Water Directive (MAC 11·3 mg $NO_3-N\ l^{-1}$,

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European Community, 1980), the new E.C. Nitrate Directive (European Community, 1991*a*) focuses on the leaching of nitrate from agricultural sources and its role in causing eutrophication of both inland and coastal waters. Where there may be a eutrophication problem, as in regions of Belfast Lough (Parker *et al.*, 1988), then the Lough must be classified as sensitive under the Urban Waste Water Directive (European Community, 1991*b*). If a significant cause of the eutrophication can be shown to be due to nitrogen compounds arising from agriculture in the catchment of the Lough, then these catchments must be designated as nitrogen vulnerable zones and appropriate remedial measures taken.

The present study describes work to aid identification of potential nitrogen vulnerable zones in Northern Ireland and also enables prediction of nitrate losses from any water catchment area in the Province. The model predicts the amount of nitrate leached to surface waters on a 10 × 10 km grid on the basis of farming intensity, nitrate deposition from precipitation and the input from the sewered human population. It draws on a variety of databases, including the annual agricultural census of farms, the human population census, leaching data from small and large experimental catchments, annual meteorological data and rainfall chemistry in Northern Ireland. The predicted values have been compared with observations from a statutory, Province-wide river-water quality monitoring programme.

As all sources of data used in the present study are spatially referenced (i.e. they have a link to a location on a map), these diverse databases are most effectively integrated, managed and analysed within a geographic information system (GIS), (Burroughs, 1986). This approach facilitates mapping of data in relation to geographic boundaries such as counties and water catchment areas. The GIS also makes possible the prediction and display of the effects of changes such as increased fertilizer usage. The 10 × 10 km grid size used is adequate for showing regional trends and has the advantages of rapid processing with minimum storage requirements, which makes it ideal for studies carried out on PCs. As equivalent datasets are available for many other parts of the world, the approach used in this study could be applied readily to other situations.

2. Methods

2.1. STUDY AREA

The total area of Northern Ireland is 1 412 000 ha, of which 1 348 000 ha is land and 64 000 ha is ascribed to inland water. It has a mean daily air temperature of 8·5°C (1951–1980 average) and an annual rainfall of 1095 mm (1941–1970 average). The geology of the area is described by Wilson (1972). The soil parent material is mostly basaltic glacial till with significant areas of silurian shales, mica-schist and carboniferous materials. The principal soil associations are climatic peat (above 200 m) and acid brown earths and gleys on the lowland. Agricultural land accounts for 80% of the total area of Northern Ireland and is dominated by grassland (72%) and rough grazing (18%), with only 6% under crops and 1% in woodland (HMSO, 1990).

The total human population usually resident in Northern Ireland was enumerated at 1 577 836 (HMSO, 1992). This is an increase of only 115 060 (7·5%) in the population enumerated in 1981. The Province is divided into six counties and its hydrology is dominated by the Lough Neagh drainage basin, which is situated centrally and occupies

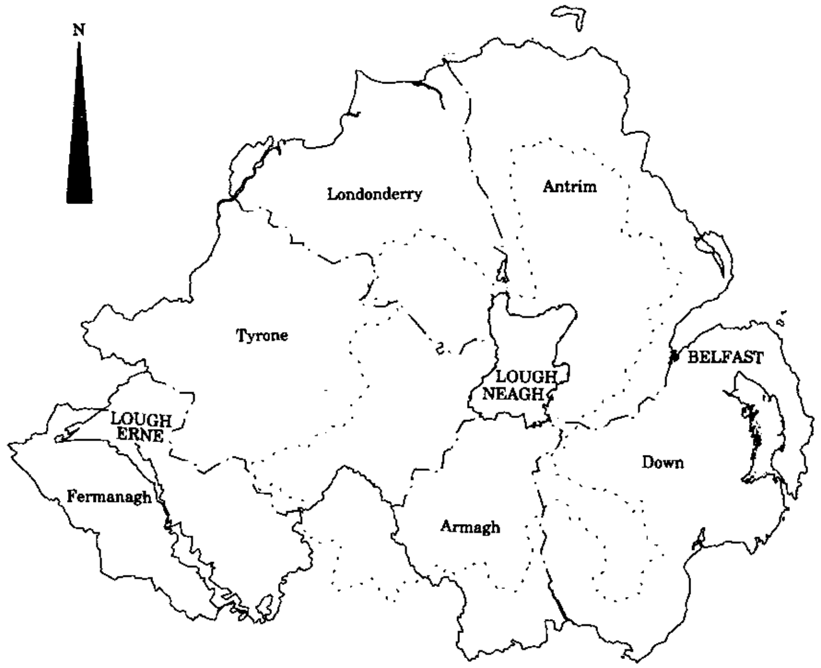

Figure 1. Northern Ireland including its major lakes (loughs), County names and boundaries —·—·— and the Lough Neagh catchment boundary -----. This map is based on digital data supplied by OSNI. © Crown Copyright.

a total area of 445 300 ha (Figure 1). Six major rivers flow into Lough Neagh, draining 88% of the total catchment.

2.2. HARDWARE AND SOFTWARE

The GIS used was a hybrid system comprising SysScan's map creation and editing software "GINIS V5.1.1" hosted on a VAXstation 4000 and Digital Resource Systems analytical GIS software "TERRASOFT V10.2" hosted on a DEC-PC433 workstation. The two halves of the overall system were networked to each other, to an A0 Altek digitizer and to an A0 Calcomp Pacesetter eight-pen plotter. Attribute data were held in tables on the relational database management system ORACLE (Version 6). The VAXstation was also linked to the Ordnance Survey of Northern Ireland's (OSNI) computer system by a 64 k "kilostream" LAN bridge. This link allowed direct transfer of digital versions of OSNI's maps from OSNI to the GIS workstation. These maps can be edited, for example to add other geographic boundaries not normally captured by OSNI surveyors, before transfer to the PC for analysis. Apart from the geometry incorporated in the base map, all datasets were stored in an ORACLE database.

2.3. BASE MAP

A digital base map of Northern Ireland was transferred across the OSNI–DANI LAN bridge to the GIS. This map was at a nominal scale of 1:250 000 and contained the international and county borders, the coastline, watercourses, lakes, forestry and road network (OSNI, Crown Copyright reserved). These data were in turn read across the network to the PC workstation where other datasets were integrated with the base map and readied for analysis and manipulation by the TERRASOFT software.

2.4. CREATION OF THEMES

In order to be able to analyse the attribute data geographically, a link between the map and the attribute data has to be made. This link usually takes the form of an association of the attribute data with given points or polygons on the map using a unique identifier for each point or polygon. In TERRASOFT jargon, this association is referred to as the creation of feature and area themes, respectively. By selecting points or polygons within such themes, the system will identify and display all the data in the ORACLE tables associated with those points or polygons. The polygons can be any shape provided they are closed.

In this study, an area theme was created using a regular 10 × 10 km grid to give a series of 100-km^2 squares. The grid reference of the centroid of each square was used as the unique identifier to which the nitrate, farm census and other data were linked. Here, for convenience, all the polygons (i.e. the 10-km grid) are square and of equal size.

The GIS can also create raster themes. These themes are composed of raster layers. Each layer comprises a regular grid of pixels each with a single associated value. In this case, there *is* a system requirement for the grid to be rectangular and to have the same shape and size over the entire map area under study. Unlike the area theme, only a single value can be associated with each part of the grid. However, groups of raster layers can be linked together into a raster theme which can then provide the same sort of information as an area theme. Raster themes have the advantage that they are much faster to process than equivalent area themes, though they take up much more storage space on the computer. Raster themes also have the disadvantage that, compared to area themes, output options to screen and plotter are more limited. Both area and raster themes were used in this study as appropriate. Data were transferred between the raster and area themes using utilities provided within the GIS.

2.5. GRID SYSTEM

All data in this study were linked to the map through their Irish Grid reference (Ordnance Survey, 1971). Data used in the present study were aggregated on a 10 × 10 km grid system, hereafter referred to as either the 10-km grid or the grid, as appropriate. The origin of this grid was located at Easting 150000 and Northing 310000 on the Irish Grid, i.e. the study origin was located 150 000 m east and 310 000 m north of the Irish Grid origin. This origin provides compatability with other maps of the Province (Partridge, 1988; Cooper and Murray, 1992; Cruickshank *et al.*, 1993), permitting a straightforward integration of such maps for overlay analysis, etc., within any future GIS. The grid covers Northern Ireland in a network of 330 grid squares. These grid squares were numbered from 1–330, starting from the origin and working up the columns (Figure 2). Note that some of these grid squares include no land area, while those around the coastline and inland loughs (Loughs Neagh and Erne) include land and water. Land areas in each grid square were calculated by the GIS by overlaying

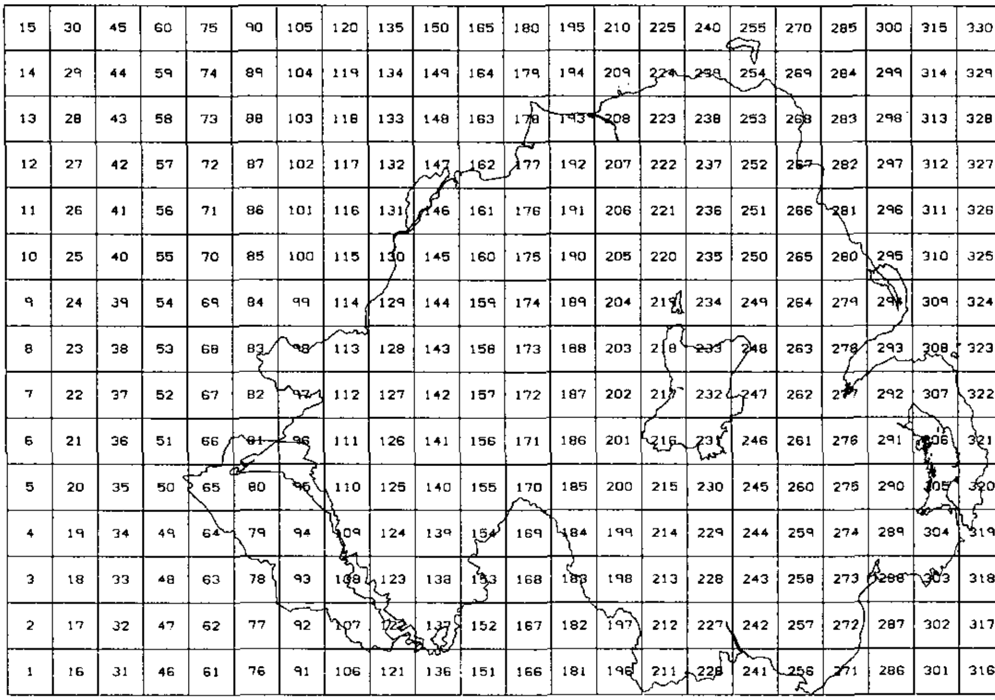

Figure 2. The 10 × 10 km grid system overlaid on the outline of Northern Ireland.

the grid on the outline of Northern Ireland, including its major lakes. Altogether, the land area of the Province is covered by 179 grid squares.

2.6. FARM CENSUS DATA

Farm census information for livestock numbers was used to infer nitrogen fertilizer usage. To protect the anonymity of this information, data were supplied in an aggregated form. For this study, data aggregated to the 10 km grid from the 1990 farm census were made available. Values of fertilizer usage in the Province over 12-month periods were also provided, covering the periods 1 June 1990 to 31 May 1991 and 1 June 1991 to 31 May 1992 (referred to as 1990 and 1991 data, respectively). The June–May period has the advantage over the calendar year in that it does not split the major nitrate leaching period of October to February.

2.7. HUMAN CENSUS DATA

The total number of persons and households across the Province and the numbers of households connected to sewers were made available from the "Small Area Statistics" database of the 1981 census on a 1 × 1 km grid by the DHSS (DHSS, 1981). This database protected the confidentiality of the data and, in addition, no data were disclosed for grid squares where the number of persons was less than 25 or the number of households was less than eight. These data were aggregated to the 10-km grid for compatability with the farm census data and stored in the same ORACLE table as used for the farm census data.

2.8. METEOROLOGICAL DATA

Maps of Northern Ireland with annual rainfall isohyets at 100-mm intervals were provided by the Meteorological Office in Belfast for 1990 and 1991. These rainfall "contours" were digitized on to the base map of the Province using the TERRASOFT digitizing module. After digitizing, the contours were processed to assign rainfall values to grid squares by an interpolation procedure. The procedure is equivalent to the creation of a digital elevation model, except that rainfall contours are used in place of elevation contours.

Penman potential transpiration (PT) values over short grass for 17 stations in Northern Ireland and two stations in the border counties of the Republic of Ireland were also provided by the Meteorological Office in Belfast for 1990 and 1991. These 19 spot values were contoured at 20-mm intervals on the GIS and the contours interpolated to assign PT values to the same grid of squares as for the rainfall isohyets.

2.9. RAINFALL CHEMISTRY

The rainfall chemistry, including a number of nitrogen fractions, at four stations in Northern Ireland has been monitored in bulk (wet plus dry) precipitation collectors by the Aquatic Sciences Research Division of DANI on a 2-week basis since January 1985. The four stations are located approximately in the north, south, east and west quadrants of the Province. Their exact location, characteristics and chemical determinands monitored are detailed by Jordan (1987). Data from these stations contributed to the secondary network of sites used to monitor acid rain in the U.K. (Warren Spring Laboratory, 1987), and this work continues. Rainfall-weighted means of nitrate concentration for 1990 and 1991 were taken from the DANI database. Methods of collection, chemical analysis and the calculation of rainfall-weighted means are detailed in Jordan (1987). These annual mean values were entered as spot values in TERRASOFT and treated in the same way as the PT data to estimate the pattern of nitrate deposition across the Province on a 10-km grid.

2.10. RIVER-WATER QUALITY MONITORING

As part of its statutory duties, the Department of the Environment for Northern Ireland [DOE(NI)] regularly monitors river-water quality at 231 stations in Northern Ireland. The rate of monitoring depends on the size of the watercourse and whether it is a source of drinking water. As a consequence, sources may be monitored weekly, 2-weekly, monthly or quarterly. The nitrate data recorded at 132 stations in 1990 and at 152 stations in 1991 were made available for this study by the DOE(NI) Environment Service. These data were read into an ORACLE database and mean nitrate concentrations calculated for each station on the grid. Where more than one station fell within a given grid square, a weighted mean (X) was calculated:

$$X = \sum_{1}^{N}(x \times n) / \sum_{1}^{N} n, \qquad (1)$$

where x is the mean nitrate value at a given station, n is the number of samples available at that station and N is the number of stations in the grid square. In this way, 71 of the 179 grid squares covering the Province were assigned observed mean nitrate concentrations for 1990. For 1991, 81 squares were assigned nitrate values.

DANI undertakes its own water quality monitoring programme of the major rivers entering Lough Neagh (Smith and Stewart, 1989). The database from this programme, which comprises weekly concentrations and loads of nitrate entering Lough Neagh for the period 1971–1991, was also made available for the present study.

3. Computations

3.1. FERTILIZER INPUTS

Since fertilizer applications were only available as an annual total across the whole of Northern Ireland, some way of allocating the fertilizer to individual grid squares needed to be determined. As crops make up only 6% of the total agricultural area, the nitrogen applied as fertilizer is essentially used to produce grass which, in turn, is used only for cattle production. This fact suggested an allocation of the annual fertilizer nitrogen applied to a given grid square on the basis of the number of cattle in that square. However, it was necessary to standardize the data in order to take account of cattle of different types (dairy, beef, bull) and ages. This was done by calculating the dairy cow equivalent (DCE) for each grid square. This conversion is a standard procedure in agricultural work when dealing with livestock of all types and ages and is detailed in Kirke and Hassard (1990). DCE values for each grid square were calculated from the agricultural census data for 1990. These data were then used to apportion the total fertilizer-N used in Northern Ireland (F in tN year^{-1}) to individual grid squares according to equation (2):

$$N_f = \frac{DCE_f}{\Sigma DCE_f} \times F, \qquad (2)$$

where N_f is the amount of N applied annually in a given grid square (in tN year^{-1}), DCE_f is the cattle numbers in dairy cow equivalents and ΣDCE_f is the total number of cattle in NI in dairy cow equivalents. In 1990, $\Sigma DCE = 1\,007\,198$ and $F = 116 \times 10^6$ kgN (HMSO, 1990), giving 115·2 kgN year^{-1} per DCE. The maximum DCE value of 12 119 corresponded to grid square 244 (nearest town is Banbridge) which, applying equation (2), is equivalent to the application of 1396 tN as fertilizer or 139·6 kgN ha^{-1} year^{-1}.

3.2. RAINFALL DEPOSITION

The contribution of rainfall deposition (in tN) to the N-input to each grid square was calculated as follows:

$$N_r = NO_3N_r \times R \times A/10^5, \qquad (3)$$

where NO_3N_r is the rainfall-weighted annual mean nitrate concentration (in mgN l^{-1}), R is the rainfall amount (in mm) and A is the land area (in ha). Values for NO_3N_r varied from 0·17 to 0·32 mgN l^{-1} in 1990 and 0·13 to 0·52 mgN l^{-1} in 1991, with values increasing as one travelled across the Province from west/north-west to south-east.

With a maximum annual rainfall of 1600 mm in 1990, this precipitation amounted to a maximum nitrate deposition of 51 200 kgN per grid square, or 5·12 kgN ha^{-1}, for that year.

The total amount of nitrate (N_t in tN $year^{-1}$) input to a given grid square from fertilizer and precipitation is given by equation (4):

$$N_t = N_f + N_r \quad (4)$$

3.3. NITRATE-N LEACHED FROM EACH GRID SQUARE

There are three main nitrogen inputs which are correlated with nitrate leached to watercourses—fertilizer, rainfall and domestic sewage (from the sewered population).

3.3.1. *Fertilizer input*

Work on both large catchments (Smith *et al.*, 1982) and experimental plots (Garrett *et al.*, 1992) in Northern Ireland has shown that, over a 12-month period, there is a good correlation between the amount of fertilizer-N applied to an area and the amount of nitrate leached. In the Lough Neagh catchment (Figure 1) which covers 4453 km^2, about one-third of the land area of the Province, modelling of nitrate leaching to surface waters over the period 1971–1987 by Smith and Stewart (1989) showed that the equivalent of 13% of the fertilizer applied to this catchment was lost in leachate. Hydrological years, October to September, were used in their work instead of calendar years, January to December, because the latter split the hydrological cycle. The coefficient of 0·13 had 95% confidence limits of 0·09 to 0·16. An extension of this model to cover the years 1969–1989 revised the coefficient to 0·14 (Smith *et al.*, 1992), while a further revision to cover the years 1969–1991 predicted a coefficient of 0·15, with 95% confidence limits of 0·11 to 0·19 (Smith, 1993, in preparation). Taking into account the confidence limits, these values show good agreement with the results of Foy *et al.* (1982), who estimated that the equivalent of 12% of nitrogen fertilizer applied was leached from the same system. Leaching data from a small experimental catchment (1·2 ha), set up to study the nitrogen cycle on grazed grassland and located at the Agricultural Research Institute, Hillsborough, Co. Down (Garrett *et al.*, 1992), also showed a linear relationship between N leached and N applied. The equivalent of 13% and 12% of the nitrogen fertilizer applied was lost as nitrate through leaching during the study years 1989–1990 and 1990–1991, respectively.

The datasets from the large and small catchments compare well with one another, but because the Lough Neagh catchment covers a much larger area and is more representative of the land use and management practices in the Province as a whole, the fertilizer coefficient resulting from the Lough Neagh study was used in the current work. Thus, the amount of nitrate leached (N_l in tN $year^{-1}$) is related to the fertilizer input of any grid square by equation (5):

$$N_l = 0{\cdot}15 \times N_f. \quad (5)$$

It is interesting to note that Meybeck (1982) also concluded in his study of nutrient transport by world rivers that about 15% of nitrogen cycled in terrestrial systems was leached to watercourses.

3.3.2. *Sewage input*

In Northern Ireland, 85% of the human population (HMSO, 1992) is connected to a municipal sewer. Nitrogen in domestic sewage is converted to nitrate as it passes through the sewage treatment works and is eventually discharged to a watercourse. Human census data were used to estimate the nitrate input (N_s in tN year^{-1}) from the sewered population (*P*, persons resident) according to equation (6a):

$$N_s = P \times 9{\cdot}1 \times 365/10^6, \qquad (6a)$$

where 9·1 is the number of grams of nitrogen per capita output daily from the sewage works (Smith, 1976). Sewage treatment works (STWs) around the Northern Ireland coastline generally discharge directly to the sea though, apart from Belfast and Londonderry, these works generally serve small populations. In Belfast, 18% of domestic sewage is discharged to the River Lagan (DOE, 1988). To allow for partial or complete discharge direct to the sea, a factor (*S*) was added to the database and set by the GIS to 0 for those grid squares bounding the coastline and to 1 for all other grid squares, except that including Belfast (grid square 277) where a value of 0·18 was used. Thus, equation (6a) becomes:

$$N_s = P \times 9{\cdot}1 \times 365 \times S/10^6. \qquad (6b)$$

Around 58 000 households, or 222 000 persons, in Northern Ireland, mostly in rural communities, are not connected to the sewage network. In these households, human waste is collected in a septic tank which discharges through a soakaway to the soil. This discharge occurs at about 2 m below the surface and, being below the rooting zone of most crops including grass, is not available to uptake by plants and is potentially leachable. This potential will be reduced by denitrification in the tank. If we assume that all the N from the unsewered population is leached as nitrate, the average contribution to the nitrate leached per grid square would be 4·4 tN year^{-1}. This average compares with 104 and 89 tN year^{-1} for nitrate leached from agriculture, 20 and 25 tN year^{-1} from rainfall and 23 tN year^{-1} from the sewered population in 1990 and 1991, respectively. Thus, the contribution to nitrate leaching by the unsewered population was considered to be insignificant in this study and no allowance for this factor was made in the calculation of nitrate leached.

3.3.3. *Rainfall*

For the purposes of this study, of the N deposited in precipitation, the equivalent of all the nitrate deposited in rainfall is considered to be leached. This conclusion follows from Smith and Stewart's (1989) nitrate leaching model for Northern Ireland. Their model predicts a loss rate of around 5 kgNO_3—N ha^{-1} year^{-1} for zero fertilizer usage, a rate which closely matches the measured input of nitrate from rainfall deposition (Jordan, 1987; Jordan, 1993, unpublished). Rainfall contained similar amounts of nitrate-N and ammonium-N (Jordan, 1987; Jordan, 1993, unpublished). Although the ammonium-N could undergo nitrification in the soil, it was not included in the calculation of nitrate leached for two reasons. First, unlike nitrate-N, ammonium-N is immobilized in contact with soil and only miniscule amounts are leached. Second, ammonium-N is taken up preferentially by perennial grass (the dominant grass type in

Northern Ireland) under soil conditions prevalent in Northern Ireland (Watson, 1986, 1987) so that the opportunities for nitrification are minimal.

These assumptions are supported by monitoring work carried out by DANI in 1990 on 1011 ha of land grazed by sheep in a remote part of the south-east of Northern Ireland (DANI, ASRD, 1990, unpublished) where no fertilizer was applied. The loss rates of nitrate-N and ammonium-N were found to be 5·2 and 0·3 kgN ha^{-1} $year^{-1}$, respectively, while the corresponding deposition rates for the same location were 4·8 and 3·8 kgN ha^{-1} $year^{-1}$, respectively. Thus, equation (5) was applied to each grid square to calculate the rainfall contribution.

The combined contributions of agriculture, sewage and rainfall to the total amount of nitrate leached (N_t in tN ha^{-1} $year^{-1}$) from any given grid square is, therefore, given by equation (7):

$$N_t = (0{\cdot}15 \times N_f) + N_s + N_r\,. \tag{7}$$

3.4. MEAN NITRATE CONCENTRATION IN EACH GRID SQUARE

To convert the amount of nitrate leached in each grid square to concentration, an estimate of the annual flow through the watercourses in each grid square is required. Over the period of a year, the effective rainfall should match the total flow through the system (W in 10^6 l $year^{-1}$) so that, for a given grid square:

$$W = (\mathrm{RAIN} - \mathrm{PT}) \times \mathrm{LANDAREA}/100, \tag{8}$$

where RAIN and PT are in mm and LANDAREA is in ha. The predicted annual mean nitrate concentration (in mgN l^{-1}) for that grid square is then given by equation (9):

$$N_c = N_t \times 1000/W. \tag{9}$$

4. Results and discussion

A GIS consisting of a computer database with spatial processing and display facilities offers unprecedented scope for relating information derived from a number of sources. In the present study, the GIS was used to predict and map nitrate loads and concentrations in leachate on a 10 × 10 km grid for Northern Ireland in 1990 (Figure 3) and 1991. Predicted nitrate concentrations ranged from 0·5 to 1 mgN l^{-1} in the poorer quality farm land in the north and west to around 5–7 mgN l^{-1} in the much better quality land in the south and east. The maximum predicted nitrate concentration of 10·08 mgN l^{-1} occurred in grid square 230 (which includes a large urban area and therefore a large sewage input) in 1991. The maximum observed mean nitrate concentration was 5·54 mgN l^{-1} in grid square 243, an area of fertile land between Banbridge and Newry.

The distributions of the predicted and observed nitrate concentrations for 1990 and 1991 largely match one another and are illustrated in Figure 4. All observed nitrate concentrations fall within the range 0–6 mgN l^{-1}, while 92% of the matching predicted values also fall within this range. Note that the range class 0–1 mgN l^{-1} is missing in the "observed" distribution. This is because DOE(NI) generally select monitoring points in the lower reaches of watercourses where water quality tends to be poorer. When all

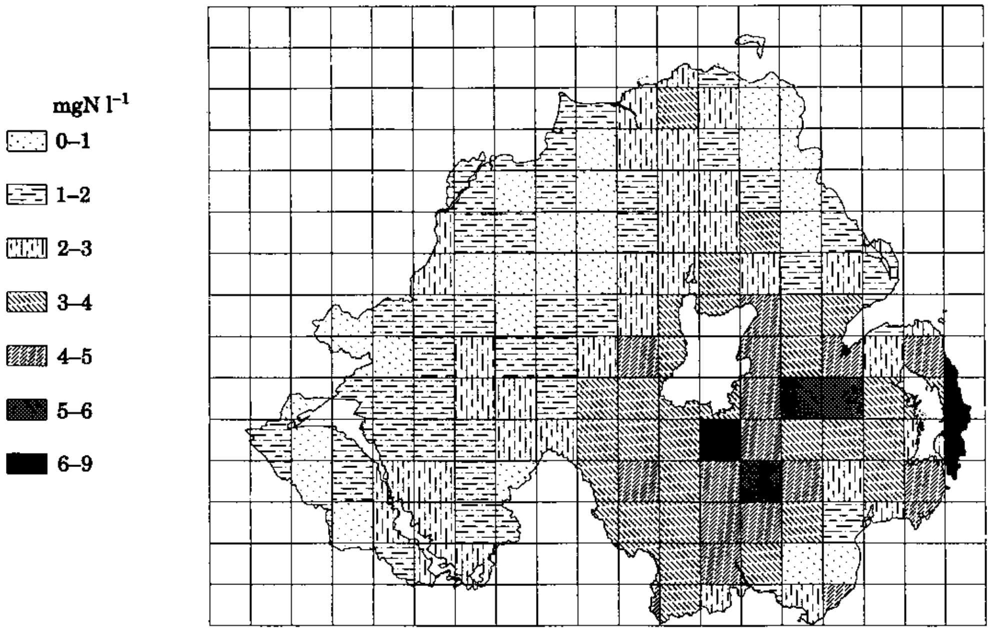

Figure 3. Predicted nitrate concentrations in surface waters in Northern Ireland by grid square for 1990.

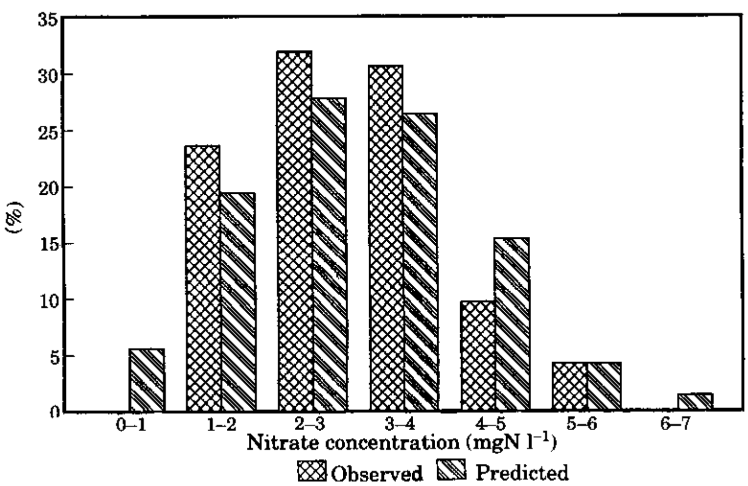

Figure 4. A comparison of the distribution of predicted nitrate concentrations for 1990 with those observed in the DOE(NI) river monitoring programme.

179 predicted values are considered, 98% of the values lie below 8 mgN l^{-1}. These values lie well within those required to comply with the E.C. Drinking Water Directive (European Community, 1980). On the basis of these data, no restrictions on current fertilizer usage in Northern Ireland are indicated for the Province to comply with the terms of that directive. One would expect little change in nitrate leaching from year to year where farm management practices and human population figures remain essentially

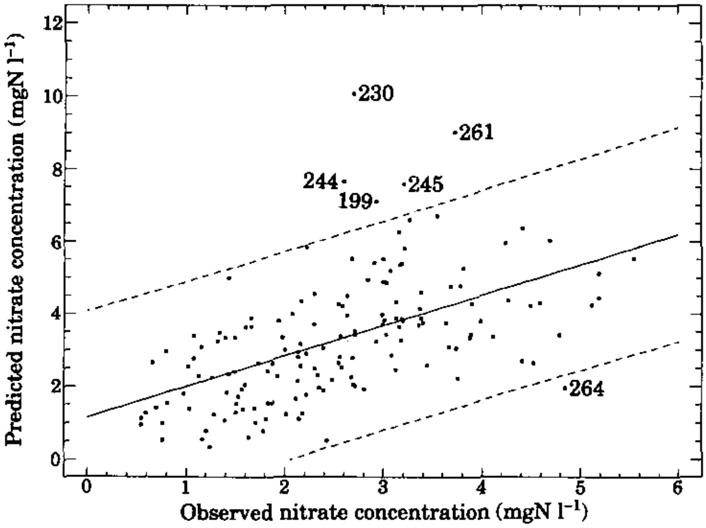

Figure 5. A plot of predicted versus observed nitrate concentrations for 1990/1991, showing the linear regression line ——— and the 95% confidence limits ---- about the regression line for this dataset. The number alongside data points lying outside the confidence limit lines refers to the grid square for which the prediction was made.

constant. In fact, the predicted nitrate concentration map for 1991 was identical to that for 1990 except that the top plotting range had to be increased from 6–9 to 6–11 mgN l^{-1} to allow for the higher maximum prediction (10·08 mgN l^{-1}) for grid square 230.

However, under the terms of the new E.C. Nitrate Directive (European Community, 1991*a*), it is also necessary to consider nitrate loads. For 1990, predicted nitrate loads in leachate for individual grid squares varied from 39·0 to 289·1 tN year^{-1} (grid squares 252 and 230, respectively), reflecting the differences in farming intensity in the grid squares involved. Grid square 230 (Lurgan area) is in a lowland area of fertile land to the south-east of Lough Neagh used largely for cattle production but with a significant input of N from domestic sewage, while grid square 252 is in a remote, sparsely populated area in the Antrim hills used mainly for grazing sheep. Predicted nitrate concentrations for the same grid squares were 0·27 and 6·27 mgN l^{-1}, respectively, in 1990. Grid squares 252 and 230 also gave the minimum (48·3 tN) and maximum (278·3 tN) predicted nitrate loads, respectively, in leachate in 1991.

For those grid squares where observed nitrate concentrations existed from the DOE(NI) river quality monitoring programme, a comparison of predicted versus observed nitrate concentrations was made for 1990 and 1991. Of the 179 grid squares covering Northern Ireland, the DOE data provided comparison values for 72 and 82 squares for 1990 and 1991, respectively. A plot of predicted versus observed nitrate concentrations, together with the 95% confidence limits from a linear regression of the data, is shown in Figure 5 for the combined years 1990/1991. The regression line in Figure 5 is given by:

$$\text{Predicted } NO_3N = 0{\cdot}84 \times \text{observed } NO_3N + 1{\cdot}15, \qquad (10)$$

$r^2 = 0{\cdot}294$, d.f. $= 152$, $P < 0{\cdot}001$***. The value for the slope (0·84) in equation (10) has

95% confidence limits of $\pm 0{\cdot}21$, so that the observed values lie within the limits of those predicted. Because nitrate concentration is estimated as the ratio of the nitrate load to flow, and the GIS predicts flow very successfully from rainfall minus PT (see later), any error in the concentration prediction is likely to come from the value predicted for nitrate load. Of the three components contributing to the nitrate load, the amount of nitrate leached in relation to fertilizer applied is generally the largest (on average 74% of the total load) and the least accurately predicted. The contribution to the nitrate load from rainfall deposition (on average 18%) is nearly twice that from sewage, except in urban areas. Because of changes in population between 1981 and 1991, the sewage contribution may be underestimated by, on average, 8% but, as the vast majority of the grid squares represent rural communities, this underestimate is insufficient to explain the differences between observed and predicted values. Closer agreement between predicted and observed could be achieved by using a higher factor than the 0·15 used in equations (5) and (7) for the proportion of fertilizer leached. In fact, a 1:1 agreement can be achieved by using a factor of 0·18, which lies within the confidence limits of the value for the proportion leached ($0{\cdot}15 \pm 0{\cdot}04$). However, it should also be recognized that the "observed" values used here are actually arithmetic means of a number of samples from, sometimes, a number of different stations within a given grid square and are themselves subject to 95% confidence limits of about 50% of their mean value. Thus, the agreement between the GIS prediction and the DOE monitoring data is good, even when the best estimate of the fertilizer factor (0·15) is used. The intercept in equation (10) has 95% confidence limits of $\pm 2{\cdot}9$ and is not significantly different from zero.

Forcing the regressed data through the origin gives:

$$\text{Predicted } NO_3N = 1{\cdot}22 \times \text{observed } NO_3N, \qquad (11)$$

$r^2 = 0{\cdot}222$, d.f. $= 153$, $0{\cdot}01 < P < 0{\cdot}001^{**}$. The closeness of the predicted and observed values will obviously depend on the location of the sampling point(s) on the water-course(s), especially where large point sources enter the system. The outliers in Figure 5, lying above the 95% confidence line, correspond to data from grid squares 199, 230, 244, 245 and 261. All five squares have a significant urban population and therefore a significant point source input. In two of these squares (230 and 261), the sewage contribution (around 60%) to the predicted total amount of nitrate leached greatly exceeds the contribution from fertilizer (around 30%) and rainfall deposition (around 10%). One might have expected this effect to have been more evident in the case of the two major cities in Northern Ireland, Belfast (grid square 277) and Londonderry (grid square 146), with populations of 314 270 and 63 472, respectively (HMSO, 1992). However, in both cases, most of their sewage is discharged direct to the sea. The GIS predicted that if all the sewage from Belfast were discharged to a surface water, the mean nitrate concentration in that water would be of the order of 20 mgN l^{-1}. As it is, with only 18% (166 tN) of its sewage discharged to the River Lagan, predicted nitrate concentrations for grid square 27 were 4·5 and 6·0 mgN l^{-1} in 1990 and 1991, respectively. These estimates compare with observed values of 5·2 and 4·7 mgN l^{-1} for 1990 and 1991, respectively. A similar comparison applies to Londonderry (observed 2·1, predicted 1·7 mgN l^{-1} in 1991).

The single outlier lying below the 95% confidence limits corresponds to grid square 264, a rough grazing area in the hills above a small market town (Ballyclare), population 6262, which lies just in the south-east corner of square 264. The cause of the discrepancy between observed and predicted is again to do with the location of the surface water sampling point. In this instance, a major river (River Sixmilewater) passing through Ballyclare was sampled. Much of this river's catchment area to Ballyclare lies outside grid square 264 and receives much of its input from good-quality farm land receiving significant amounts of fertilizer to the south east of this square, i.e. the predicted values for square 278 (3·1 and 3·6 mgN l^{-1} for 1990 and 1991, respectively) should more closely match the observed values for square 264 (4·85 and 4·53 mgN l^{-1} for 1990 and 1991, respectively).

As well as comparing predicted and observed concentrations, it was also possible to compare predicted nitrate loadings to surface waters with observed loads. For example, by digitizing in the boundaries of the Lough Neagh catchment area and overlaying this polygon on the predicted nitrate loading theme, it was possible to calculate a cumulative value for the annual amounts of water and nitrate leached from this catchment area. In this way, the annual loading of nitrate to Lough Neagh was predicted to be 8601 ± 1779 and 7880 ± 1518 tonnes for 1990 and 1991, respectively. The predicted values include a pro-rata allowance for the 10·2% of the catchment area that lies within the Republic of Ireland and for which DCE and population data were not available—it was assumed that values for this area were the same as the average values in the Northern Ireland portion of the Lough Neagh catchment. The observed nitrate loss rates from DANI's routine monitoring programme for Lough Neagh for 1990 and 1991 were $10\,155 \pm 1016$ and 7612 ± 761 tonnes, respectively. These observed values lie within the confidence limits of those predicted. The components of the predicted annual nitrate loading to Lough Neagh for 1991 correspond to losses of 5693 tN from agriculture, 1306 tN from rainfall deposition and 882 tN from sewage.

Predictions of annual water discharge through the Lough Neagh catchment, based on rainfall minus PT, were very good. Annual flows for this catchment were predicted by the GIS to be 3146 and $2313 \times 10^6\,m^3$ in 1990 and 1991, respectively, compared with measured values of 3040 and $2485 \times 10^6\,m^3$, respectively. Repeating the exercise for the six individual river catchments discharging to Lough Neagh shows a similar level of agreement between predicted and observed loads and flows as for the whole catchment (Table 1).

One would expect that, as the catchment decreases in size, predicted and observed values would start to differ significantly. Unfortunately, due to lack of suitable calibration data, we could not investigate this aspect thoroughly. However, Table 1 does include a comparison between observed and predicted nitrate loads and flows for, what is on the 10-km grid, a small catchment of only 14·9 km^2 (Foy, 1991). The latter is a sub-catchment of the River Upper Bann and straddles grid squares 244 and 259 in Figure 2. The prediction of both annual flow and nitrate loading for 1990 is, surprisingly for a catchment area equivalent to only 0·15 grid squares, on a par with that for catchments of 2 grid squares and above. It can be seen from Table 1 that predicted annual flows are generally $\pm 10\%$ of those observed. However, nitrate loads predicted using a factor of 0·15 in equations (5) and (7) predominantly underpredict by, on average, 22% in 1990 and, excluding the River Blackwater, by 11% in 1991. Some of this underprediction can be corrected for by increasing the fertilizer factor used in equations (5) and (7) to its upper confidence limit of 0·19. The final column in Table 1 gives the value to which the fertilizer factor must be increased in order to match the predicted load with that observed. In some cases, this value lies outside the limits (0·11 to 0·19) of that used in Smith and Stewart's model (Smith *et al.*, 1989, 1992)—see Section 3.3.1 of this paper. This difference is believed to be due to the effect climatic, cropping and soil factors

TABLE 1. A comparison of predicted and observed annual flows and nitrate loads for a range of catchments in Northern Ireland in (a) 1990 and (b) 1991

(a)

Catchment	Area (km^2)	Observed		Predicted		Predicted/observed		Factor† to give pred./obs. = 1
		Flow ($10^6 m^3$)	NO_3N load (tN)	Flow ($10^6 m^3$)	NO_3N load (tN)	Flow (%)	NO_3N load (%)	
River Sixmilewater	297·5	224·9	710·6	205·5	552·2	91·4	77·7	0·21
River Main	706·6	629·7	1946·3	647·7	1293·1	102·9	66·4	0·25
River Moyola	323·5	324·6	758·0	321·9	473·0	99·2	62·4	0·27
River Ballinderry	433·4	312·3	1127·9	321·9	854·5	103·1	75·8	0·21
River Blackwater	1568·7	875·9	2871·8	978·9	2828·1	111·8	98·5	0·15
River Upper Bann	686·7	299·1	1494·8	367·6	1391·7	122·9	93·1	0·16
Lough Neagh	4453·0	3040·0	10156·7	3146·0	8601·0	103·5	84·7	0·19
Experimental area	14·9	6·4	52·6	8·3	35·3	129·7	67·1	0·23

(b)

Catchment	Area (km^2)	Observed		Predicted		Predicted/observed		Factor† to give pred./obs. = 1
		Flow ($10^6 m^3$)	NO_3N load (tN)	Flow ($10^6 m^3$)	NO_3N load (tN)	Flow (%)	NO_3N load (%)	
River Sixmilewater	297·5	182·0	561·7	141·4	497·8	77·7	88·6	0·18
River Main	706·6	536·6	1567·7	466·9	1181·3	87·0	75·4	0·22
River Moyola	323·5	274·5	621·7	244·7	450·5	89·1	72·5	0·23
River Ballinderry	433·4	239·6	823·8	263·3	783·8	109·9	95·1	0·16
River Blackwater	1568·7	681·5	1810·1	717·8	2565·6	105·3	141·7	0·09
River Upper Bann	686·7	265·9	1292·5	278·6	1292·7	104·8	100·0	0·15
Lough Neagh	4453·0	2485·3	7612·3	2313·0	7880·0	93·1	103·5	0·15
Experimental area	14·9	n.a.	n.a.	6·4	32·1	—	—	—

† Leaching factor used in equations (5) and (7) to adjust the predicted nitrate load to match that observed.
n.a. = not available.

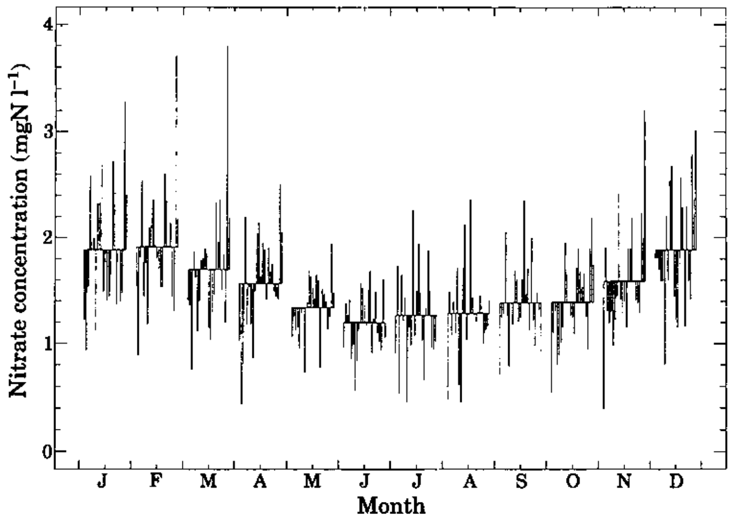

Figure 6. Observed monthly mean nitrate concentrations for the River Blackwater for the period January 1969 to December 1991. The horizontal bars are the overall means for each month for the period 1969–1991. The 13 vertical lines associated with each horizontal bar indicate, from left to right, the actual monthly means for each of the years 1969 to 1991.

play in determining the total amount of nitrate leached from any given catchment (Smith *et al.*, 1989, 1992; Allanson *et al.*, 1993).

The model used in the present study makes no allowance for such factors. The current model also does not take account of losses of nitrate within the water system. If such losses occur, the observed nitrate load will be less than that predicted by the model. This effect was observed in only one instance, that of the River Blackwater in 1991. It is significant that the River Blackwater has the largest catchment area of the Lough Neagh inflows. As a result, the residence time of nitrate in this water course is increased and there are greater opportunities for losses to occur, for example by plant uptake (Isenhart and Crumpton, 1989) or denitrification (Hill and Sanmugadas, 1985). Data from the DANI river monitoring programme support this hypothesis. During the summer months, mean nitrate concentrations were observed to decline significantly in the River Blackwater (Figure 6).

Having validated the predictive capabilities of the model used to calculate nitrate load, the nitrate loads to surface waters were estimated for the Province by counties (Table 2) for 1990 and 1991. The nitrate loss rate values per unit area in Table 2 show an interesting contrast between the western counties, especially County Fermanagh in the far west, and the eastern counties (see Figure 1). The differences arise largely from the lower sewage contribution and lower stocking densities supported on the less productive land in the west of the Province. Lower nitrate leaching losses in County Fermanagh have been reported by Jordan (1989) and were attributed to a combination of less intensive agriculture, reduced mineralization/nitrification of organic matter and increased opportunity for denitrification. However, the latter two factors must not play too big a role in determining the overall nitrate leaching loss because levels predicted using the present model compare favourably with those observed (Figure 5), even though the two factors are not accounted for in the model.

Loss of nitrate has both environmental and economic consequences. Based purely

TABLE 2. Predicted annual flows and nitrate loads by county and for Northern Ireland as a whole for 1990 and 1991

Catchment	Area (km^2)	Predicted 1990			Predicted 1991		
		Flow ($10^6 m^3$)	NO_3N load† (tN)	Load/area (kgN ha^{-1})	Flow ($10^6 m^3$)	NO_3N load† (tN)	Load/area (kgN ha^{-1})
County Antrim‡	3075·5	2226·3	4718·9	15·3	1570·0	4330·6	14·1
County Down	2479·4	1200·6	4120·1	16·6	939·7	3850·7	15·5
County Armagh	1328·7	626·4	2414·9	18·2	443·8	2212·8	16·7
County Fermanagh	1855·3	1498·5	2172·0	11·7	1088·2	1968·9	10·6
County Tyrone	3300·6	2837·2	4884·0	14·8	2194·1	4539·1	13·8
County Londonderry	2077·9	1840·3	2721·2	13·1	1327·8	2566·0	12·3
Sewage NO_3N to sea	—	—	1581·1	—	—	1581·1	—
Northern Ireland	14117·4	10229·3	22612·2	16·0	7563·6	21049·2	14·9

† Excludes the nitrate load from domestic sewage which is discharged direct to sea.
‡ Belfast included.

TABLE 3. Percentage contribution of agriculture, rainfall and domestic sewage†; to the total nitrate load in Northern Ireland on a county basis for 1990 and 1991, based on data summarized in Table 2

County	1990			1991		
	Agriculture (%)	Rainfall (%)	Sewage (%)	Agriculture (%)	Rainfall (%)	Sewage (%)
Antrim	64·3	12·8	11·5	59·2	16·2	12·4
Down	65·2	11·6	9·3	59·0	16·5	9·8
Armagh	76·2	10·5	13·3	70·9	14·5	14·5
Fermanagh	81·9	14·6	3·5	77·1	19·0	3·8
Tyrone	79·6	15·4	5·0	73·1	21·5	5·4
Londonderry	69·7	16·5	3·4	62·7	22·7	3·6

† Including NO_3N from domestic sewage discharged direct to sea.

on the cost of around £0·40 per kilo of N and the summary data in Table 2, the value of the nitrate leached to the environment annually is around £8·8 million for the Province as a whole, or £6·50 for each and every hectare of land in Northern Ireland. The contribution of each of the three components determining the overall nitrate loss, agriculture, rainfall deposition and domestic sewage, is detailed in Table 3, on a county basis for 1990 and 1991. It can be seen that around 70% of all nitrate lost to watercourses originates from agriculture. In the more densely populated counties in the eastern half of the Province, the remaining 30% of the nitrate load originates approximately equally from rainfall and sewage. By contrast, in the less populated western half of the Province, the remaining 30% of the nitrate load originates predominantly from rainfall which dominates the sewage contribution by a factor of about 5:1. Thus, NO_x emission reductions will have a more pronounced effect in reducing nitrate levels in surface waters in the west of the Province than in the east. In the western counties, the rainfall: sewage ratio should approach 1:1 over the next 10 years as planned reductions in emissions from power stations and vehicular exhausts throughout Europe, including the U.K. and Ireland, take effect.

5. Conclusions

The present study has shown that a GIS provides new opportunities in analysis of data which have a spatial component. For example, mapping the data on a 10-km grid allows one to observe variations in farming activity, human population densities, sewered and unsewered populations and meteorological conditions on a regional basis. The power of being able to do this rather basic exercise within a GIS environment is often underestimated. For example, in the present study, it was possible to map the unsewered population density Province-wide, producing a product which could be used to assess the environmental impact of, say, tourist developments on the trophic status of Northern Ireland's large lakes.

However, the full potential of the GIS approach goes much further than pure mapping because it is possible to see how individual data layers interact with one another by linking relevant themes through modelling. In the present study, a model of nitrate leaching was developed which, after validation with observed data, made it possible to predict nitrate losses from individual catchment areas to within about 25%. This level of prediction provides adequate management information for a preliminary screening of which catchments should be targetted for designation under the Nitrates and Urban Waste Water Directives (European Community, 1991*a*,*b*). The model has the potential for further development such as moving to a 1-km^2 grid, the inclusion of climatic, soil and nitrate loss terms, together with the incorporation of a digital elevation model to investigate the effect of altitude, slope and aspect on nutrient losses. However, such considerations lay outside the scope of the present study.

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